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Genetic Algorithm Application for the Optimization of Solid State Devices using a Novel Modeling Technique

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***Abstract*— A new method for developing a realistic physical model of any type of solid state device is presented. Application to model advanced multi-junction solar cells; Thermo-photovoltaics; sensors; as well as other novel solid state devices are introduced in this presentation. The primary goal of multijunction solar cell design is to maximize the output power for a given solar spectrum. The construction of multijunction cells places the individual junction layers in series, thereby limiting the overall output current to that of the junction layer producing the lowest current. The solution to optimizing a multijunction design involves both the design of individual junction layers which produce an optimum output power and the design of a series-stacked configuration of these junction layers which yields the highest possible overall output current. This paper demonstrates the use of Genetic Algorithm in a two-part process to refine a given multijunction solar cell design for near-optimal output power for a desired light spectrum. This approach can similarly be utilized to optimize the parameters of any Solid state device to yield any desired performance.**

I. Introduction

THE optimization routines described in this paper use a solar cell model developed earlier at the Naval Postgraduate School (NPS) using the ATLAS device simulator by SILVACO International [1]. This model accurately predicts the electrical characteristics of a solar cell based on virtual fabrication of its physical structure.

As an example demonstrating this modeling technique, a triple-junction InGaP/GaAs/Ge solar cell is modeled, and the device light-induced photogeneration, and the corresponding spectral response of each layer are illustrated in Figures 1 & 2. A detailed paper introducing this Novel modeling technique has been previously presented [2].The performance and results produced from the virtually fabricated MJ model, are very similar to those published in [3] as well as in many other papers [4-7]. The results are also comparable to experimental data of similarly manufactured cells, Figures 3 & 4. Minor differences are only due to the variations in the material and optical parameters used. If needed, those can easily be tuned to reflect experimental results more accurately.

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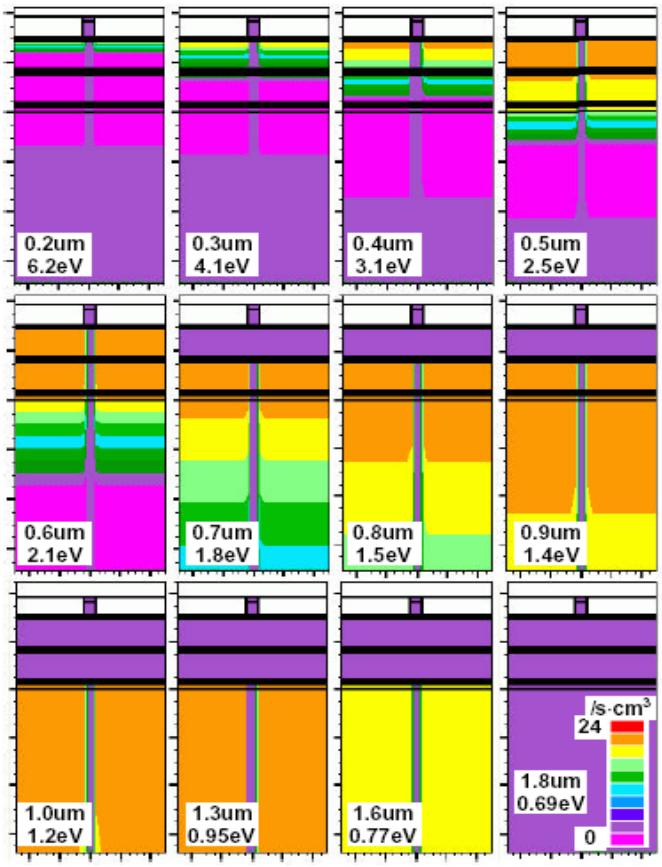

Figure 1. ATLAS photogeneration rate output for a multi-junction solar cell for different light wavelengths.

Figure 2. Spectral response of the individual cells (dashed) and of the stacked cell (continuous).

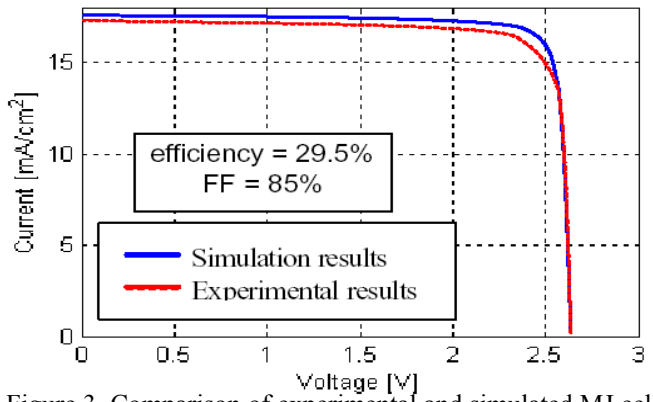

Figure 3. Comparison of experimental and simulated MJ cell *IV* characteristics.

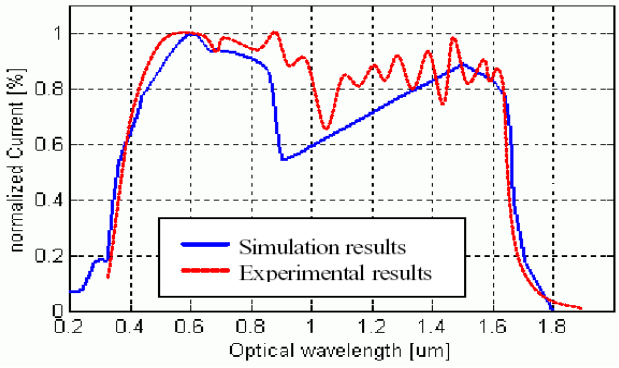

Figure 4. comparison of experimental and simulated MJ cell spectral responses.

II. THE GENETIC SEARCH ALGORITHM

Earlier research, at NPS, demonstrated the capability of utilizing the developed solar cell models to optimize MJ cell's output power by varying different layer thicknesses using an exhaustive search algorithms [8]. As expected, the reported results verified some of the parameters and data of current MJ cell designs that were previously obtained through years of research, experimentation and fabrication. Effects of other cell parameters, such as doping level, different bandgap materials and others were also researched.

The first step in the optimization process is to maximize the output power of each junction layer individually for several layer thicknesses. These optimum configurations will be used to ensure maximum junction layer output power as junction layer thicknesses are changed during the current-matching process. The junction layer optimization process accepts known materials for the window, emitter, base and back surface field (BSF) and determines the ideal thicknesses and doping levels for each region. The base thickness was chosen to be a dependent variable to achieve a constant overall junction layer thickness. Thus, eight independent variables remain for each overall junction layer thickness. To search all possible solutions rigorously would require an enormous amount of computational time. Instead, a genetic algorithm was used to search the solution space for the junction layer configuration producing the highest output power.

To enact a genetic algorithm for junction layer optimization, each of the eight variable junction layer parameters was encoded into a four-bit binary string. The encoded binary strings, referred to as genes, were then assembled into 32-bit binary chromosomes.

Fig. 5 below, illustrates the construction of 32-bit binary chromosome from a gene sequence. Each chromosome fully encoded the eight variable properties of a junction layer. A set of 32 randomly selected binary strings made up the initial generation of chromosomes. The encoded properties in each of these chromosomes were used to construct and simulate a junction layer in ATLAS under AM0 illumination. After the simulation of an entire generation of chromosomes, child chromosomes (to make up the next generation) were formed from a mix of the genes from the best performing parent chromosomes. Each parent chromosome was ranked according to the P_{max} of its associated junction layer using an elitist roulette wheel selection mechanism [9]. Child chromosomes were formed from parents using a two-point crossover operation [9] as shown in Fig. 6. Bit-inverting "mutations" occurred in each child chromosome according to some small probability to add genetic variety (Fig 7). A relatively small population size was used with recommended crossover and mutation probabilities [9]. In addition, the best performing chromosome of each generation was passed unchanged onto the next generation.

The genetic search algorithm was allowed to progress for a maximum of 20 generations. This scheme allowed a solution space of over 268 million junction layer designs to be searched to arrive near an optimal junction layer configuration for a specific thickness. Figure 8 demonstrate the improvement in the cell output power.

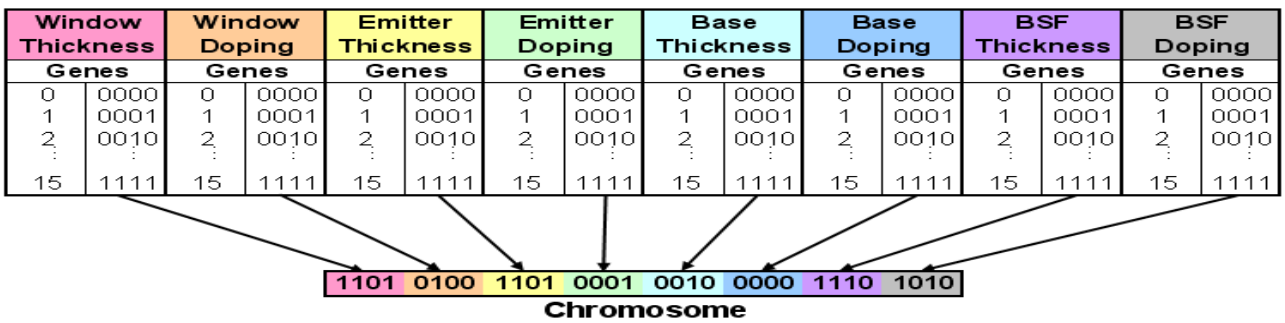

Figure 5. Construction of binary chromosomes from gene sequences.

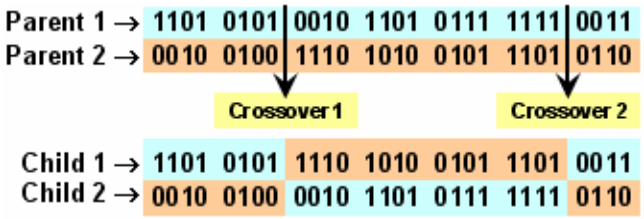

Figure 6. Two-crossover genetic mixing

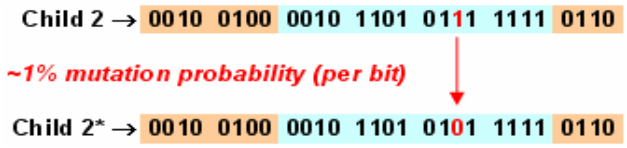

Figure 7. Bit-inverting mutation.

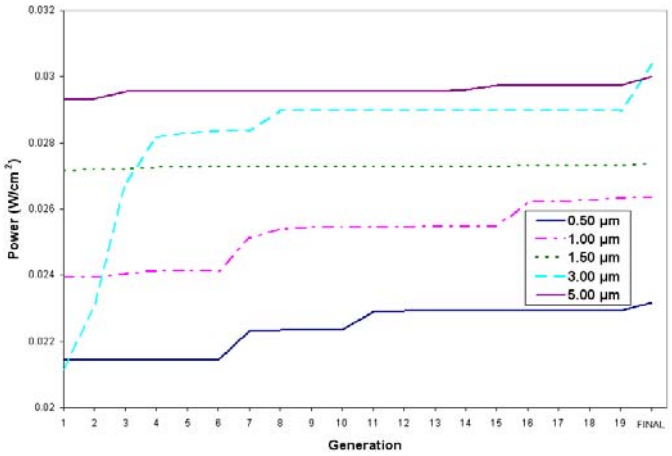

Figure 8. Improving the GaAs junction layer output power.

III. ITERATIVE CURRENT MATCHING ROUTINE

To achieve a maximum overall output current from the full multijunction cell, the current produced by each junction layer needed to be matched to the fullest extent possible. To accomplish this, we used an iterative current-matching routine beginning with an ATLAS simulation of the full multijunction cell with each junction layer thickness larger than its estimated final thickness. In this initial state, each junction layer absorbed a large amount of light and little light energy was able to penetrate to each lower junction layer successively.

To match short-circuit currents, junction layers were grouped into pairs from the top junction to the substrate junction (Figure 9). Short-circuit currents were matched within the pairs by either increasing or decreasing the thickness of the upper junction layer.

Then the junction layers were re-grouped with the other adjacent junction layer and the process repeated iteratively until the short-circuit currents of all junction layers were within 99.6% of each other. At this point, the routine changed focus to attempt to match the maximum-power currents of the individual junction layers.

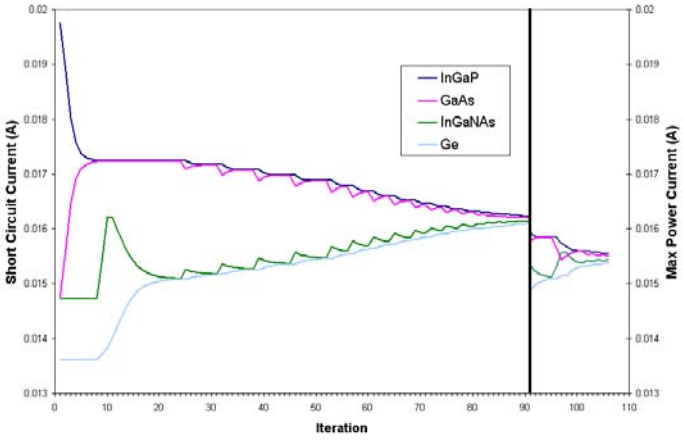

Figure 9. Progress of iterative current matching.

The routine ceased when all junction layer maximum-power currents were matched. The optimum cell configuration could then be determined by a review of the output file for the cell with the highest overall maximum power (Figures 10,11).

It was necessary to ensure that each junction layer performed optimally at each of the many thicknesses used in the iterative current-matching routine. This was accomplished by using the optimized parameters from the genetic search algorithm for each junction layer. When a junction layer thickness was required that had not been specifically solved for during junction layer optimization, interpolation between known optimum values was used.

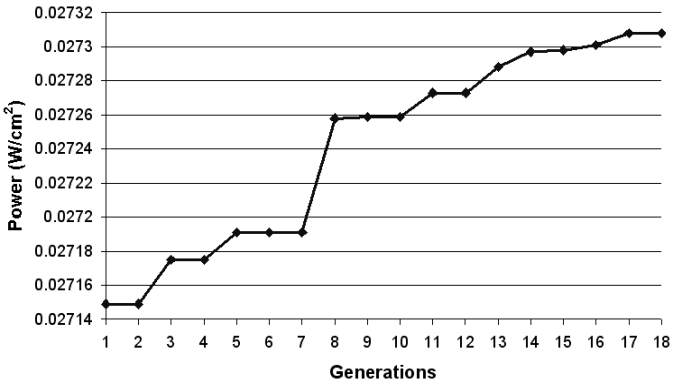

Figure 10. Maximum output power for the GaAs junction layer versus successive genetic algorithm generations.

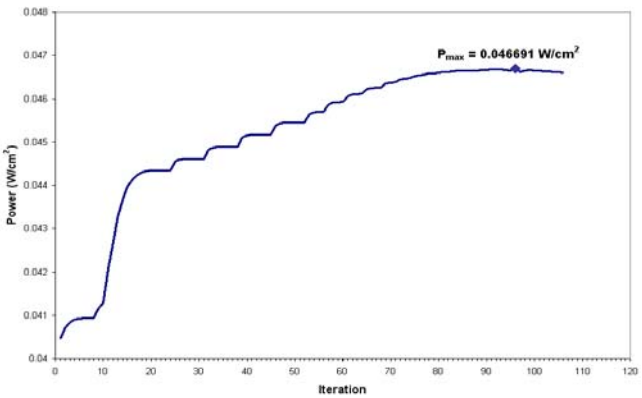

Figure 11. Optimum 3-junction cell output power.

IV. RESULTS

For obvious reasons of propriety, no published reports on the detailed construction of advanced three- and four-junction solar cells could be found. This lack of an experimental baseline complicates any attempt to show the improvement over a tested design obtained by using the optimization procedure proposed in this paper. The advantage of this technique is instead demonstrated using unpublished three- and four-junction solar cell designs that have been realized using ATLAS. Figures 12 & 13 illustrate the optimized triple-junction cell structure and its *I-V* output.

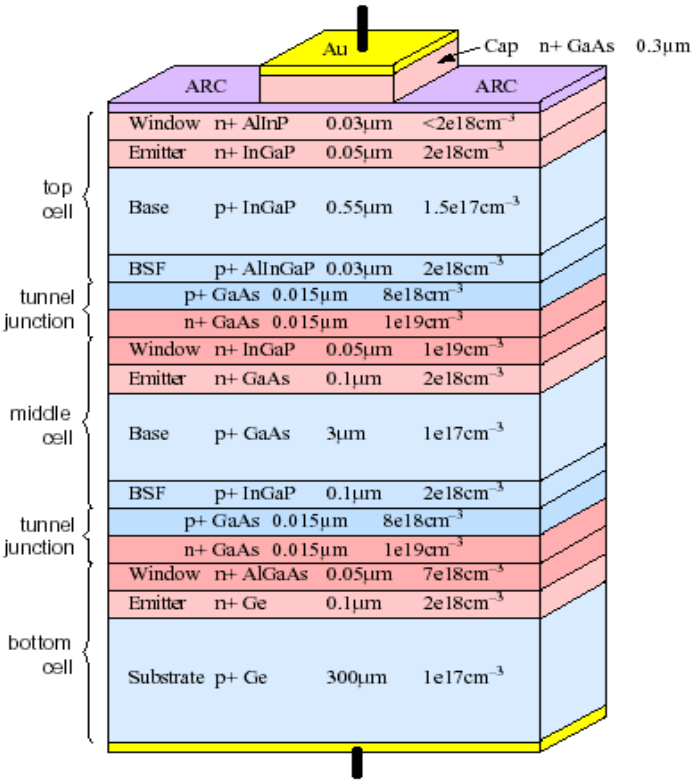

Figure 12 The Optimized new triple-junction cell structure.

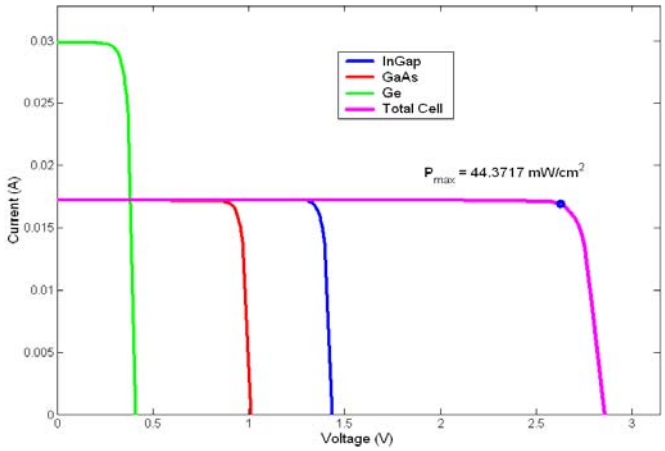

Figure 13 The *I-V* curves for the optimized 3-junction cell.

The same optimization approach was applied to a novel quad-junction solar cell that was designed and presented in reference 10]. The model generated *I-V* characteristics of the optimized Quad-junction cell are presented in Fig. 14 below, which clearly shows the unprecedented output power achieved using these optimization efforts.

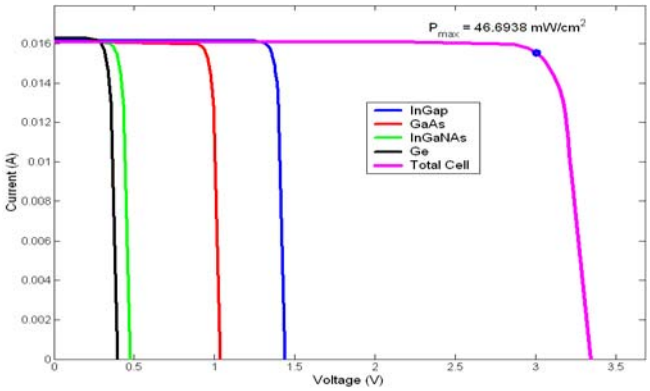

Figure 10 *I-V* curve for optimized 4-junction.

The improvements as a result of this optimization approach for the quad-junction solar cell is summarized in Figure 15 below.

Figure 15 Maximum power comparison of the optimized quad-junction cell and the novel cell proposed in [10].

The successful efforts presented here using advanced multi-junction solar cell designs, which achieved devices with record conversion efficiencies, can be similarly used to optimize many solid state devices at a very moderate cost.

V. CONCLUSION

The combination of the genetic and iterative algorithms presented in this paper and the ATLAS device simulator show great promise for streamlining the design of optimized multijunction solar cells. The complex interactions between the various thicknesses and dopings of the materials available to the solar cell designer make determination of an absolute optimum configuration difficult. The genetic search algorithm we have presented has shown the ability to search an extremely large solution space to arrive at a near optimal solution without user interaction. The routine is scalable to any large population size and number of generations limited only by computational time. In addition, the process will optimize a multijunction cell to whatever applied spectrum. Through a simple modification to the spectrum used in this paper, the technique could be changed to optimize the MJ cell to the Martian surface spectrum.

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